APPENDIX.

Anode circuit.—Referring to Figs. 2 and 3, and ignoring the circuit $L_3R_3C_3$ in Fig. 3, put

$$
\begin{aligned}
E &= \text{E.M.F. in the valve,}\\
E_1 &= \text{E.M.F. across } C_1,\\
E_2 &= \text{E.M.F. across } L_1,\\
I &= \text{current through the valve,}\\
I_1 &= \text{current through } C_1,\\
I_2 &= \text{current through } L_1.
\end{aligned}
$$

Then

$$
\begin{aligned}
I &= (E - E_1)/A\\
I_1 &= jE_1C_1\omega\\
I_2 &= E_1/(R + jL\omega)\\
&= E_2/jL\omega\\
I &= I_1 + I_2
\end{aligned}
$$

If ϕ is the phase angle between E_2 and E, then it can be shown that

$$\tan\phi = \frac{-A(LC\omega^2 - 1) + R}{L\omega + ARC\omega} \quad . \quad . \quad . \quad (26)$$

Now put $\omega = \omega_0(1 + y)$ and we get

$$\tan\phi = \frac{-2Ay + R}{\sqrt{(L/C)} + AR\sqrt{(C/L)}}$$

which is the form of equation (2) on page 39.

Anode oscillatory circuit.—A combination of the results shown in equations (29) and (2) leads to the result

$$\tan\phi = -\frac{2Ay\sqrt{(L/C)}}{(L/C) + AR}$$

which is the form of equation (3) on page 39.

Acceptor circuit.—The circuit is supposed to consist of a coil of inductance L and resistance R in series with a capacity C.

The complex resistance of the whole circuit is $\{R + j(L\omega - 1/C\omega)\}$, and the phase angle between current and E.M.F. is

$$\text{arc tan}\,\frac{LC\omega^2 - 1}{RC\omega}$$

The potential across C lags 90° behind the current, and the phase angle between this potential and the applied E.M.F. is given by the equation

$$\tan\theta = \frac{RC\omega}{LC\omega^2 - 1}$$

where θ is an angle between 180° and 360°.

If ω is near the resonant frequency ω_0, put $\omega = \omega_0(1 + x)$, where x is a small quantity, then

$$\tan\theta = \frac{R\sqrt{C}}{2x\sqrt{L}}$$

which is the form of equation (4) on page 40.

DISCUSSION BEFORE THE WIRELESS SECTION, 6 JANUARY, 1926.

Major A. G. Lee: For some time past it has been recognized that an ordinary valve transmitter is liable to large frequency-changes which are caused by unavoidable variations in filament current and anode voltage. In order to overcome this difficulty I have devised another solution * which consists in obtaining harmonics from a valve-maintained tuning-fork oscillator, selecting a particular harmonic and amplifying it for transmission from the antenna as the wireless frequency. This system is now in use at the Northolt, Devizes and Rugby valve stations. The author has attacked the problem more directly and fundamentally. It may be of interest to get a physical idea of the processes involved in these frequency-changes which have been worked out mathematically and experimentally in the paper. The simplest case to analyse in this fashion is that of the tuned grid, untuned anode, oscillator. If we start with a voltage E_g of a certain phase on the grid, there will be an E.M.F. in the anode circuit of $-\mu E_g$, the minus sign denoting 180° phase change. Now, if the anode circuit were resistive only, the current in that circuit would be in phase with the E.M.F., and this would in turn produce an induced E.M.F. in the grid tuned circuit of phase $+$ 90°. The current in the tuned circuit due to this E.M.F. would be in phase with it, and therefore the voltage across the condenser, which is also that across the grid and filament, would be in phase with the E.M.F. we started with, E_g. Now if we have regard to the actual conditions in the anode circuit we see that, due to the inevitable inductance coil in it, the current is out of phase with the E.M.F. generated in the anode circuit by the valve. This out-of-phase current may be regarded as introducing a reactive component into the tuned circuit, and if we desire to retain the original frequency of E_g from which we started, we can correct the phase by mistuning the circuit. Actually what is happening is that the system oscillates at some frequency other than that to which the circuit is tuned. Now we can see that if any changes of filament current or anode voltage occur, of sufficient magnitude to alter the anode resistance, the phase of the current in the anode circuit will be altered and the circuit will oscillate on a different frequency. This phase effect is the major one of the several causes, referred to in the paper, which operate to change the frequency of oscillation. The remedy for the "phase" effect is to ensure that the grid and plate alternating voltages are always 180° apart in phase, and the conditions for this adjustment have been worked out in the paper. If, for example, in the above-mentioned case of an untuned anode, the anode circuit were resistive only, any alteration of anode resistance would not change the phase, and no alteration of frequency would result. Figs. 2, 4 and 5 are of interest because they are all circuits with two degrees of freedom, and we should expect, at first sight, to have two modes of oscillation. In the case of Figs. 2 and 4, however, the phase relation-

* A. G. Lee: "Tuning-fork Generator at Northolt," *Electrician*, 1925, vol. 94, p. 510.

ships are such that the circuits will not oscillate on one of the modes of oscillation. In Fig. 5, when the two circuits are identical, there is again only one mode of oscillation possible, that in which the current circulates round the inductances and capacities in the circuit. The current does not pass through the resistance, because the two ends of the resistance are at the same potential (with actual physical circuits possessing resistance there will be a small difference of potential across the ends of the shunting resistance and a small current will pass through it). The other type of possible oscillation, in which the main current passes through the shunting resistance, puts the grid and anode at the same potential, a condition in which the valve will not maintain oscillations. This is also a very interesting circuit to analyse physically. It may be regarded as a development of the Colpitts oscillator, Fig. A. In this circuit the

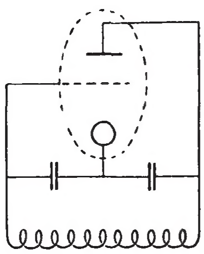

FIG. A.

grid-filament and anode-filament resistances may be represented as resistances shunted across the two condensers, as shown in Fig. B. It is fairly easily seen that these shunting resistances will affect the frequency of oscillation, and if they vary in magnitude with the voltage of supply the frequency generated will also vary. The author's solution is to join the points A, B, by a small resistance so as to bring these points to nearly the same potential, and the theoretical circuit corresponding to this case is shown in Fig. C. It will be seen

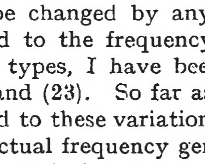

FIG. B.

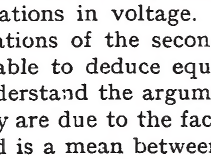

FIG. C.

that the valve resistances are now symmetrical with regard to both the capacities and inductances and the circuit will oscillate at its natural frequency, which will not be changed by any alterations in voltage. With regard to the frequency variations of the second and third types, I have been unable to deduce equations (21) and (23). So far as I understand the argument in regard to these variations, they are due to the fact that the actual frequency generated is a mean between that obtained during the portion of the cycle when the valve is passing current and the other portion when it is not passing current. Also any changes which affect the length of the fraction of a cycle during which current is passed will affect the value of the mean frequency. It would therefore appear that equations (21) and (23) should contain an expression for the valve conductances as affecting the phase and, therefore, frequency generated. A circuit which would appear to give most of the conditions for constant frequency is the " Dynatron " circuit. This circuit would appear to be free from the major variation due to phase shift. I think that the able analysis of the effects causing frequency shift made by the author will be of considerable assistance in the design of short-wave oscillators and heterodyne wave-meters.

Mr. G. Shearing: The experimental results for a low-power valve generator given in Part VI of the paper comparing the frequency-changes of the various types of circuits with capacity, inductive, and resistance coupling, are very interesting and they appear to favour on the whole the adoption of the resistance type of coupling with subsidiary compensating coupling for stray capacity for a constant-frequency generator. On the other hand, the remarks under the heading of " Practical Applications " leave one rather in the dark as to which type of circuit the author would really adopt for a constant-frequency generator. For the resistance type of coupling, e.g. thats hown in Fig. 10 and stated to be applicable to transmitters, master oscillators and wave-meters, I do not think it is clear that the circuit would be a very

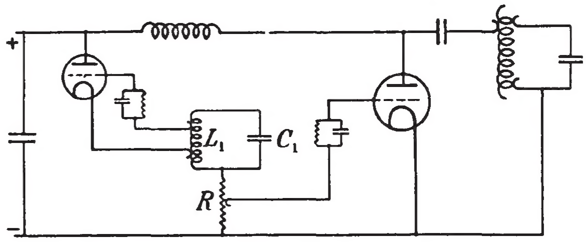

FIG. D.

efficient power generator of any magnitude, for, if the circuit C_2L_2 only carries a small proportion of the main oscillatory current, I should expect the power loss in the resistance R to become considerable for even a medium-power transmitter. On the other hand, if the circuit C_2L_2 carries a current of value equal to or greater than that in R, then the size and cost of the circuit C_2L_2 may become considerable for a small power loss. Also, how would the author couple such a circuit to the next stage of a power-amplifier system? Would he couple the grids of the next stage to the resistance R or to the inductance L_1 or capacity C_1? In this connection some of the disadvantages which appear to be attached to the use of the circuit of Fig. 10 for power amplifiers can be overcome by using the unidirectional pulses of valve current rather than the oscillatory current itself for exciting the next stage. The method of effecting this is to generate oscillations in a local oscillatory circuit L_1C_1 placed in series with a resistance R as shown, which carries only the unidirectional pulses of valve current which excite the oscillatory circuit L_1C_1 (see Fig. D). This resistance is not in the local oscillatory circuit, consequently for a suitable high-voltage supply the ohmic loss in this resistance is small. If, now, the grid or grids of the next stage of the power amplifier are connected to this resistance R, the arrangement will function satisfactorily as a power amplifier, the energy required for the grids of this stage being supplied from

this resistance, which in turn receives the energy direct from the high-tension supply. I have found such a power-amplifier arrangement to oscillate with excellent stability and a large step-up ratio; the power loss in the resistance is small by reason of the small proportion of the exciting current to the oscillatory current in L_1C_1. The constancy observed of the wave-length generated has been better than that observed for similar circuits when using inductive or capacity in place of the resistance coupling. As regards the development of a wave-meter circuit, a form of circuit has been described by E. Fromy * in which series inductances and capacities are placed in both grid and anode circuits of the generator valve; these are both coupled inductively to a separate circuit (see Fig. E). All three circuits are tuned to the same frequency and he states, giving experimental results, that, if $L_1C_1 = L_2C_2 = (L + L')C$ with coupling of L_1 and L_2 respectively to L and L' such that the grid and anode voltages are 180° out of phase, then the frequency $f = 1/[2\pi\sqrt{(L + L')C}]$ and is independent of normal changes of anode and filament voltages. The three capacities C_1, C_2 and C may be equal, and he suggests for a wave-meter that they be mounted on a common axis for ease of adjustment. The constancy of the frequency is claimed to be due to the introduction of the condensers C_1, C_2, i.e. tuning the grid and anode circuits so that they are equivalent to resistances only.

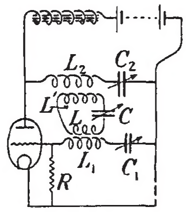

FIG. E.

Variations that may be due to changing the valve itself can be made small by using a capacity in parallel with the grid-anode capacity, and the accuracy is stated to be of the order of 0·001 per cent. The importance of grid and anode oscillatory potentials being at a phase angle of 180° is clearly indicated by the mechanical analogy and other portions of the paper. I do not understand what the author means by the term "E.M.F. generated in the valve," as surely any oscillatory E.M.F. is generated in the reactive portions of the circuits to which the valve is connected and not in the valve itself. The importance of small grid damping has been clearly pointed out in the paper, and as regards power transmitters it is more easy to arrange for small grid damping with power-amplifier circuits with grids operated definitely at a small mean potential than with retroactive circuits. For the circuit of Fig. 5 it is easy to see that the grid-filament and anode-filament oscillatory P.D.'s have the correct phase relation of 180°, but the circuit of Fig. 2 when used as a power transmitter constitutes an inefficient arrangement unless the product L_2C_2 is very much less than the product L_1C_1. The circuit as shown is applied to reception, but in this case the retroactive coupling of grid to anode, usually by means of auxiliary coils, is very small. I do not like the use of the term "complex resistance" in the Appendix, as it appears to me the author might equally well have spoken of "complex reactance." I consider that the correct term "impedance" should be used. Also, I think it much better to use the terms resistance, inductance or capacity coupling than to introduce the terms employed by the author for the circuits he has described.

* *L'Onde Électrique*, 1925, 4ᵉ année, p. 433.

Dr. R. L. Smith-Rose: One of the most important problems in the practice of wireless communication to-day is that of the reduction of interference. Two of the contributory causes of interference are (1) that transmitting stations are not on the wave-length (or frequency) allocated to them, and (2) that their transmissions vary in frequency about the mean on which they usually operate. The author refers to this matter but does not give any actual figures, and I should therefore like to draw attention to some of the results obtained at the National Physical Laboratory on measurements obtained some time ago and extending over a period of about 2 months. The measurements were made by Mr. Dye, and a summary of the results was given in the N.P.L. Annual Report for 1924 (p. 79). Some 23 transmitting stations, situated on either side of the Atlantic, were measured, most of them being high-power long-wave stations. The results show a very high degree of uniformity, and in general the variations were less than the actual difference between the mean frequency and the frequency allocated to the station. For example, 10 of the 23 stations showed a mean daily variation of less than 1 part in 1 000, which is quite large compared with the ideal conditions visualized by the author. The actual limits of the mean daily variations were from 0·2 to 3·7 parts in 1 000, whereas the actual difference between the mean frequency and the nominal frequency ranged from 0·1 to as much as 11·4 parts in 1 000 for the 23 stations. Those measurements were only carried on for a period of 2 or 3 months, but they seem to give an idea of the order of the variation which is occurring at the present time. In connection with the rheodyne circuit mentioned in the paper, I do not quite understand what would happen if the two circuits are slightly detuned from one another. Supposing one is detuned a little, to the order of a few parts in 10 000. It would seem that the system would then have two possible oscillation frequencies, and some doubt might exist as to which of these it is operating upon at any given time.

Lieut.-Col. H. P. T. Lefroy: Dr. Smith-Rose has referred to the variation in transmission frequency that occurs on the longer wave-lengths; those that occur on the shorter wave-lengths are still greater, so that any improvements in transmitter design, such as those suggested by the author, which, in a simple manner, will eliminate such variations, will be particularly valuable for small portable sets. For signal discrimination we have at our disposal, in the case of radio-telegraphy, three well-known methods, namely, high-frequency selectivity, low-frequency selectivity and directional selectivity. In practice we can usually only employ high-frequency selectivity, and, in certain cases, directional selectivity, when receiving from portable transmitters. If we try to employ low-frequency

selectivity we find that the note selectors available are quite effective, but that the heterodyne note of the received signals varies so much that the note selector filters out a large proportion of the desired signals, so that we lose the advantage of this available third method of discrimination. Master oscillators have been developed which give satisfactory constancy of transmission frequency, but they increase too much the complication and size and weight of portable sets. Is the author satisfied that his methods can be immediately applied to transmitters up to about 2 kW without serious loss of efficiency, and that such methods can be usefully employed with transmitters that have to work over a wide band of wave-lengths? As regards wave-meters, is it possible, with those made to his design, to continue to use the original calibration scale without perceptible error, after the valve has been changed owing to the filament burning out?

Mr. A. G. Warren: The particular criticism that I have to make is with regard to the author's method of working out the circuit of Fig. 3. He says:—"The problem can be simplified by assuming that the energy absorbed in the grid circuit is negligible compared with the energy absorbed by the anode circuit, so that the flow of current in $L_3R_3C_3$ can be ignored in dealing with the circuit $L_1R_1C_1$." Looking at these circuits it appears that the circuit $L_3R_3C_3$ is a circuit of low impedance, whereas L_1 is of high impedance, and therefore one would expect that the current through the

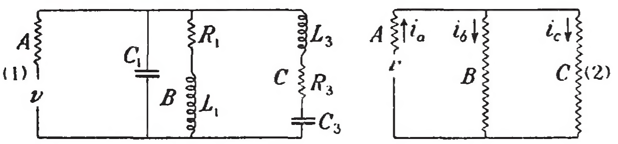

FIG. F.

shunt circuit $L_3R_3C_3$ would be considerable. It is, in fact, considerable unless the coupling between the two circuits is very small. I would suggest another way of dealing with the circuit. Assuming that R_1 is small compared with ωL_1, we may re-draw Fig. 3 as Fig. F [(1) and (2)]. For this circuit we have

$$v = i_a\left(A + \frac{BC}{B+C}\right) \quad \text{and} \quad i_a = i_c\left(1 + \frac{C}{B}\right)$$

whence

$$v = i_c\left\{A + C\left(1 + \frac{A}{B}\right)\right\}$$

Now since C contains the grid condenser (or its equivalent), i_c must be 90° out of phase with V. Therefore the expression $A + C\{1 + (A/B)\}$ must be wholly imaginary, or its real part must be zero. But

$$C = R_3 + j \,.\, 2x\sqrt{\frac{L_3}{C_3}}$$

and

$$\frac{1}{B} = \frac{C_1}{L_1}\left\{R_1 + j \,.\, 2x\sqrt{\frac{L_1}{C_1}}\right\}$$

Substituting these values, making $L_1C_1 = L_3C_3$, and equating the real part of $A + C\{1 + (A/B)\}$ to zero, we obtain

$$x = \pm\sqrt{\left[\frac{R_2C_2}{4AC_1} + \frac{R_1R_2C_2}{4L_1} + \frac{M^2C_2}{4L_1^2C_1}\right]}$$

Comparing this with the author's equation (7) we see that it includes an extra (third) term. I do not know how this third term compares with the others in practice, but, assuming an R valve with a grid circuit not exceeding a few ohms in resistance, it is greater than the first term unless M is less than 1 per cent of L_1. I imagine that M exceeds this value and that this third term is by no means negligible.

Mr. G. W. N. Cobbold: The author has directed attention to a subject of great and growing importance, upon which little has been published for several years. Attention must be called, however, to the work of Eccles and Vincent published in the *Proceedings of the Royal Society*, A, 1920, vol. 96. p. 455, where a description is given of practical experiments somewhat similar to those described in the present paper. There appear to be certain discrepancies between Eccles's results and those of the author, but I think these are probably due to the fact that Eccles placed the lower limit for his high tension at about 70 volts, whereas the author has limited his low tension to 4·2 volts. This, for the particular coupling he used, did not enable him to reach a stationary value on the frequency/low-tension-voltage curve. These differences are rather important, for the author has concluded that stationary values cannot be obtained when the filament voltage is varied, whereas Eccles has shown that, with suitable couplings and a normal type of circuit, such values can be arrived at. One of the earlier speakers appears to have suggested that the frequency-changes due to voltage variations are apt to be large compared with those due to a change of valve. I find, however, in practice, that with well-designed circuits the variations due to a change of valve are liable to be very much greater than those due to a 10 per cent change of either high-tension or low-tension voltage.

Prof. C. L. Fortescue: With regard to the resistance-coupled circuit, this merely consists of two "acceptors" in series with the resistance connected across the nodes of potential. As is well known, this circuit arrangement has a high resistance at frequencies other than that to which the "acceptors" are tuned. The arguments used in deriving equation (6) are incomplete, in that only the phase relations are considered. In actual fact there must be a magnitude adjustment, with the result that the amplification factor of the valve is necessarily involved and the anode resistance—the A of this paper—must be regarded as a variable.

Mr. C. F. Phillips: The author speaks of an accuracy of 1 part in 50 000, but I should like to know whether such an accuracy is really readable on any wave-meter, what kind of variable condenser is used, and how it is read to the requisite accuracy to give 1 part in 10 000, let alone 50 000, and further, to what extent such condenser maintains its accuracy.

Major B. Binyon: Without detracting from the value of the paper, it should be pointed out that there are other factors quite apart from filament and supply variations which might cause greater frequency variations than 1 part in 50 000. In view of the increasing use of short wave-lengths the whole question of maintaining a constant frequency is a matter of very great importance.

Mr. L. B. Turner (*communicated*): The subject under discussion is the reduction to a minimum of those very small changes in the frequency of a triode oscillator which are apt to be caused by small changes in the supply voltages. In view of the use of the heterodyne at very short wave-lengths the subject has considerable practical importance. Now the possible circuit arrangements of a triode oscillator are many. Mathematical investigation of the exact frequency can be undertaken only for sensibly sinusoidal conditions, and therefore with amplitudes small enough to allow the anode-filament resistance A of the triode to be treated as constant throughout the cycle; and even then, except in the simplest circuit arrangements comprising only a single approximately resonating circuit, the algebra is hopelessly cumbersome. The effect of change of filament or anode voltage is to alter A, generally at the same time making A rather less perfectly constant during the cycle. In order to investigate the effect on the frequency f, we need an expression for f in terms of A and of the circuit dimensions. A number of such expressions are derived in the paper, but the electrical theory behind the formulæ seems to me altogether inaccurate, and the formulæ obtained are certainly sometimes erroneous. I propose to indicate some of the mistakes as I seem to see them. With reference to Fig. 2, the author states (in the advance copies of the paper *): " The circuit $L_1R_1C_1$ being a rejector circuit, its complex resistance is . . ." Such a statement is meaningless unless the place of application of the E.M.F. is specified. As here used, $L_1R_1C_1$ is a rejector circuit as regards the " E.M.F. generated in the valve," but it is at the same time an acceptor circuit as regards the E.M.F. impressed in L_1 from L_2. The author seems here, as elsewhere in the paper, to disregard reaction of the L_2 current on L_1, appearing to think this justified " by assuming that the energy absorbed in the grid circuit is negligible compared with the energy absorbed by the anode circuit." This vitiates any search for small departures of frequency from the simple $4\pi^2f^2 = 1/LC$, which is the purpose of the investigation. A formula, (8), for the frequency is thus derived, for the particular case of $L_1C_1 = L_3C_3 = L_2C_2(1 - M^2/L_1L_2)$. Even if this formula were correct, how could one in practice adjust for $L_1C_1 = L_2C_2(1 - M^2/L_1L_2)$; why is this particular adjustment of special interest; and if it is, why, in the analogous case of Fig. 4, is the different special case of $L_1C_1 = L_2C_2$ taken ? I am unable to quote manageable correct expressions for the frequency in the cases of Figs. 2 and 4 [equations (8) and (15)], and I regard these as circuits which should be avoided, i.e. when $L_1C_1 \doteq L_2C_2$. They are too difficult in mathematical analysis and in practice, for the reason that a slight change in f or L or C may turn a large positive reactance into a large negative reactance. I cannot accept the author's gross approximation (page 40, top of col. 2) that the reactance of C_3 is negligible in comparison with the impedance of $L_2R_2C_2$. C. Gutton, in his clear and accurate discussion of triode oscillators in " La Lampe à Trois Electrodes " writes of the arrangement of Fig. 4: " Its characteristic equation is of too high a degree to be easily discussed "—a sentiment which experience has taught me heartily to endorse. With reference to Fig. 5, which is one arrangement for obtaining resistance retroaction, the statement is made that " the frequency is independent of the magnitude of the various resistances," including presumably the anode resistance A, the only one whose effect interests us; but in Fig. 17 large observed alterations of frequency with alterations of filament and anode voltages are shown. I cannot follow the author's reasoning in Part III. This professes to investigate non-sinusoidal conditions, but formulæ (21) and (23) are given—whence they are obtained is not stated—which cannot relate to such conditions, since they do not contain any term expressing the properties of the triode. Probably they refer back to sinusoidal conditions; but if so, again they are erroneous. The correct expressions are :—

For (21), $$f_1 = \frac{1}{2\pi}\sqrt{\frac{1}{C_2[L_2 + (R_2/A)L_1]}}$$

and for (23), $$f_1 = \frac{1}{2\pi}\sqrt{\frac{1 + (R_1/A)}{C_1L_1}}$$

For the former, see Gutton, loc. cit., page 92. For the latter, see Gutton, page 59; or Van Der Bijl, " Thermionic Vacuum Tube," page 274; or Turner, " Outline of Wireless," page 127. The experimental observations are interesting, but they are not used to check the theoretical formulæ. It is not clear from what frequency the plotted " frequency change " is measured. For example, in Fig. 18, where perfect insensibility to filament change was obtained, why is the ordinate steady at 2 instead of at 0 ? It suggests that the " change " plotted is the difference between the oscillation frequency and the natural or resonant frequency of the oscillatory circuit when the triode is made inactive, as by extinction of filament. If so, perhaps the author would explain how he was able to determine the latter with anything like sufficient accuracy, i.e. to a fraction of 1 part in 10 000, or 0·01 per cent.

* Since revised.

Lieut.-Col. K. E. Edgeworth (*in reply*): Several speakers have questioned the validity of various approximations made in deriving the formulæ given in the paper, and it appears desirable that my attitude with regard to this question should be defined. I may therefore explain that the whole treatment in the paper is intended to be qualitative rather than quantitative. The formulæ are intended to show the character of the frequency variations which are liable to occur, and it is not suggested that they are suitable for making exact calculations in particular cases. Apart from other difficulties the value of the quantity A, representing the anode resistance, is not known and cannot be measured, although a rough estimate might possibly be attempted. It may be defined as the reciprocal of the mean conductance of the anode circuit of the valve taken over a complete cycle of oscillation, and such a definition serves to convey some of the difficulties which would be encountered in trying to estimate its magnitude.

There remains the question : To what extent can the results produced by these various approximations be accepted at all ? The only reasonable way to answer this question would appear to be by an appeal to experi-

ment. If the results indicated by the theory are reproduced in practice, then the theory may be accepted as a working hypothesis until something better is offered. Further, a theory based upon an assumption which is known to be true in a special case may be verified by experiment, and may then be extended, by reason of experimental support, to the more general cases in which the original assumption can only be regarded as a rough approximation. The theories which I have put forward in the paper appear to provide reasonable explanations for the results of my experiments. Time will show whether they can be usefully employed in a wider field.

Major Lee draws attention to the fact that formulæ (21) and (23) do not contain any term involving the valve conductance. The explanation is that the equations refer to the resonant frequency of the tuned circuits employed in deriving equations (6) to (8), and they do not refer to the actual frequency of the oscillations generated. It is agreed, however, that the argument is not very satisfactory, and it might be amended to read as follows:—

Variations of the second type.—In the case of an orthodyne generator with tuned grid and untuned anode the equations given in Part II are modified by writing $\tan\phi = A/(L_1\omega)$ and equation (8) becomes

$$\omega = \frac{1}{\sqrt{(L_2\sigma C_2)}}\left\{1 - \frac{R_2L_1}{2AL_2\sigma}\right\}$$

$$\therefore f_1 = \frac{1}{2\pi\sqrt{(L_2\sigma C_2)}}\left\{1 - \frac{R_2L_1}{2AL_2\sigma}\right\} \quad . \quad . \quad (21a)$$

This equation gives the frequency of the oscillations when the valve is active. The corresponding equation for an antidyne generator with untuned anode is given by writing $\tan\phi = -AC_1\omega$, and then

$$f_1 = \frac{1}{2\pi\sqrt{(L_2\sigma C_2)}}\left\{1 + \frac{R_2C_2}{2AC_1}\right\} \quad . \quad . \quad (21b)$$

In either case, when the valve is inert the frequency is

$$f_2 = \frac{1}{2\pi\sqrt{(L_2C_2)}} \quad . \quad . \quad . \quad . \quad . \quad (22)$$

The factor $1/\sqrt{\sigma}$ in equation (21) is always greater than unity, and its influence on the actual frequency of the oscillations depends upon the proportion between the period of activity and the period of inertness. The argument then proceeds as before.

In the case of the frequency variations of the third type the explanation of the meaning of equation (23) is the same, but some of the approximations used in deriving the equation appear to be erroneous. This question is dealt with more fully below in my reply to Mr. Turner.

Mr. Shearing inquires as to the best type of circuit for constant-frequency generators. I have slightly altered the original wording of the paper to make this point clear. On the question of efficiency the paper contains the rather bald statement that the loss of energy in the resistance is equal to the loss of energy in the grid circuit. The actual analysis on which this statement is based was omitted, as it is rather lengthy and did not appear to be of sufficient importance to be given in detail. It can, however, be made available if required. I have no figures available as to the amount of power absorbed by the grid circuit in actual generators, but I do not think it usually exceeds 10 per cent of the power developed in the anode circuit. The anode circuit of the rheodyne generator could no doubt be coupled to the grid circuit of another valve by any of the well-known methods usually employed for this purpose. Questions of frequency variation due to change in the reactance of the load are beyond the scope of this paper.

I have not experimented with the Fromy circuit, but am inclined to think that the three separate tuning adjustments would be troublesome in practice.

The assumption that the valve can be regarded as a source of energy has, I think, been used by other writers. The actual source of energy is, of course, the high-tension battery, and the valve is a variable resistance. The method attributes to the valve exactly the same properties as those assumed in the investigations quoted by Mr. Turner.

I cannot agree that the word "impedance" is the correct name for the expression $(R + jL\omega)$, and I would direct attention to an article by Prof. Howe in the January number of *Experimental Wireless*, in which the correct meaning of the word "impedance" is explained. In regard to the new words suggested in the paper, it seems better to coin new words when required, instead of using existing words in several different and inconsistent meanings.

The observations on the wave-lengths of existing transmitting stations given by Dr. Smith-Rose are very interesting and show that there is considerable room for improvement. My experiments indicate that rheodyne circuits can be made to oscillate at two frequencies in much the same way as other circuits, and the result is no doubt due to slight mistuning.

In reply to Col. Lefroy, I am of opinion that the rheodyne generator described in the paper and also the orthodyne generator with untuned grid are both capable of being designed to cover a wide band of frequencies, and I have worked out such details as appear to be likely to influence the design. Most of the important points are referred to in the paper.

When a valve is changed there may be a change of anode resistance and/or a change of capacity. The constant-frequency circuits referred to in the paper are essentially circuits in which the frequency is independent of the anode resistance, and it is evidently immaterial whether the change of anode resistance is due to change of valve or change of supply voltage. Changes of frequency due to changes of valve capacity are of course a different matter, and a discussion of the problem would be beyond the scope of the present paper.

Mr. Warren's difficulty is due to his assumption that the circuit $L_3R_3C_3$ is a circuit of low impedance. When grid and anode circuits are both tuned a very loose coupling is sufficient to generate oscillations, so that the circuit is actually one of high impedance. When grid bias is used the energy absorbed by the grid circuit may be very small indeed, and cases have been brought to my notice in which the grid current is only a few

micro-amperes. It will be seen from the experimental results that changes in grid damping affect the magnitude of the frequency variations but not their general character, and one is therefore able to say that results based on the assumption that the grid current is small are applicable to cases in which the grid current is appreciable. The attempt to improve on my formula by the addition of an extra term might perhaps be referred to Mr. Turner, whose remarks on the complexity of the problem are very much to the point. In any case the extra term would not affect the general argument.

Mr. Cobbold draws attention to the investigations of Eccles and Vincent. The generator employed was an orthodyne generator with untuned grid, and it was found in certain cases that the curve giving the relationship between filament voltage and frequency rises to a maximum and then falls again. It would appear from Fig. 7 of the paper that the phenomenon only occurs when the coupling is very weak. The curves obtained for stronger couplings resemble those given in the paper. In practice there must always exist some factor which limits the amplitude of the oscillations, and the controlling factor is not necessarily the same with strong and weak couplings. There is a very interesting field for investigation in this direction which I have not attempted to explore.

From my remarks at the beginning of this reply, it will be seen that I am in agreement with Prof. Fortescue as to the complexity of the problem and as to the reservations which must be made in regard to the various arguments brought forward in the paper.

In reply to Mr. Phillips the simplest method of increasing the accuracy of the readings is to reduce the band of frequencies covered, by employing a small variable condenser in parallel with a large fixed condenser. If the scale can be divided effectively into 500 parts, it is immaterial whether it is employed to read from 300 to 800 m with an accuracy of the order of 1 in 500, or whether it is used to read from 495 to 505 m with an accuracy of 1 in 25 000.

I quite agree with Major Binyon that there are other problems which require solution in connection with the constant-frequency generator. Perhaps someone will tackle some of them at a future date.

I fully agree with Mr. Turner's views as to the complexity of the general problem, but I am not prepared to agree with his attitude towards approximations. It is not possible to determine the validity of an approximation by an argument in general terms. An approximation involving errors of 5 per cent is better than an approximation involving errors of 10 per cent, and an approximation involving errors of 10 per cent or even 20 per cent is better than nothing at all. In tackling an apparently simple problem like the design of a connecting rod, it may be necessary to make more than one assumption involving errors in excess of 20 per cent. To label an assumption a "mistake" or a "gross approximation" does not settle the limits within which it is capable of being usefully applied. Mr. Turner's attitude towards particular approximations is not consistent. He objects to the assumption that the energy expended in the grid circuit is small, and then puts forward a solution which ignores the grid circuit altogether!

The formula suggested in place of equation (21) of the paper omits the factor $1/\sqrt{\sigma}$ which results from the coupling, and is limited to generators using normal coupling. With these two corrections the formula is equivalent to the one which I have given in my reply to Major Lee. For our present purpose the corrections happen to be vital.

The formula suggested in place of equation (23) is limited to the ideal case in which there is no grid current, but the two formulæ should agree, and I have been led to revise the method of obtaining $\tan\phi$, the expression for which now contains an additional term. I agree that equation (23) is fallacious.

The new equation for $\tan\phi$ gives the solution quoted by Mr. Turner as a special case, and leads to a very interesting solution for the constant-frequency orthodyne generator with untuned grid, which appears to be of sufficient importance to be set forth in detail.

In the case of an orthodyne generator with untuned grid, $\tan\theta = -R_3C_3\omega = -R_2C_2\omega = -R_2C_2/\sqrt{(L_1C_1)}$, which gives

$$y = \frac{1}{2A}\left\{R_1 - \frac{R_2C_2}{C_1}\right\} - \frac{R_1R_2C_2}{2L_1}$$

$$\therefore f = \frac{1}{2\pi\sqrt{(L_1C_1)}}\left\{1 + \frac{1}{2A}\left(R_1 - \frac{R_2C_2}{C_1}\right) - \frac{R_1R_2C_2}{2L_1}\right\}$$

The frequency will be independent of the anode resistance when $R_2C_2 = R_1C_1$ or more fully when $R_4C_2 + L_2\sigma/G = R_1C_1$, which is the constant-frequency generator under sinusoidal conditions. It is difficult to say whether the solution is of much practical importance, but it is suggestive and might be made the basis for further research. It will be observed that there will usually be a difference between the frequency of the oscillations when the valve is active and the frequency when the valve is inert. When the two terms involving the anode resistance cancel out, the difference will be in the sense already discussed in the paper.

In reply to Mr. Turner's last question, the curves given in the paper represent frequency-changes only, and the zero has no significance. It may be added that the various curves which are plotted for convenience on the same diagram are not necessarily referred to the same zero.